Low Gravity Cryogenic Liquid Acquisition for Space Exploration

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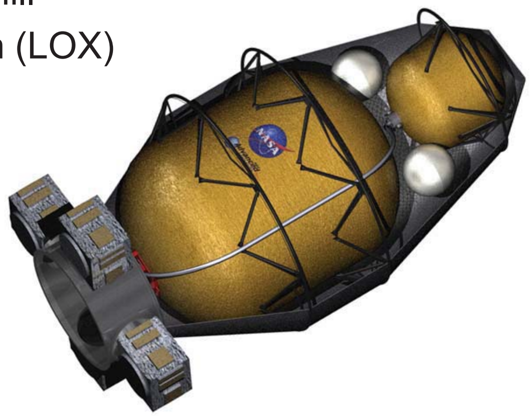
Cryogenic Propellant Technology Development

To enable cryogenic propellant depots, the Cryogenic Propellant Storage and Transfer (CPST) project has developed a plan to raise the Technology Readiness Level(TRL) of numerous Cryogenic Fluid Management (CFM) technologies:

FY11-13 Technology Maturation Ground Testing (TRL 5)

- Liquid Hydrogen (LH2) Radio Frequency Mass Gauge (RFMG)
- Multi-Layer Insulation (MLI) Penetration Degradation
- Liquid Nitrogen (LN_2) & LH_2 Liquid Acquisition Device (LAD)/Transfer Line Chill
- Active Thermal Control (Reduced Boil-Off LH2 & Zero Boil-Off Liquid Oxygen (LOX)
- MLI Vibe Test



Technology Demonstration Mission

- Demonstrate in-space storage and transfer of cryogenic propellants (TRL 6)

Cryogenic Depots for future manned and robotic missions (TRL 9)

LAD Overview – Fundamental Fluid Physics

Subsystem requirement - transfer vapor free propellant from a tank to the transfer line en route to an engine or receiver tank (depot)

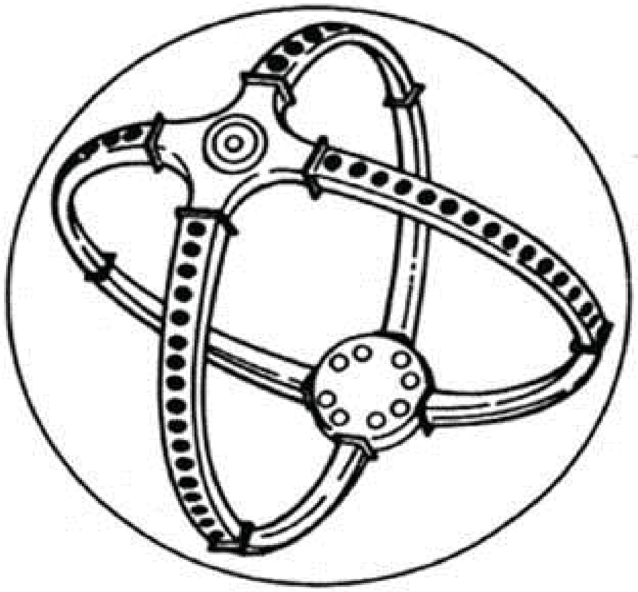
Separation of liquid and vapor phases governed by lowest achievable potential energy state

Fluid transfer in 0-g

- Surface tension force is the driver
- Liquid → outer walls , vapor → center

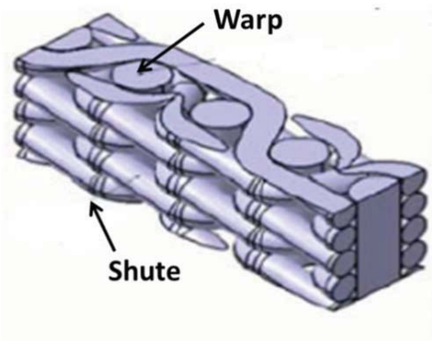
Single phase flow strategy:

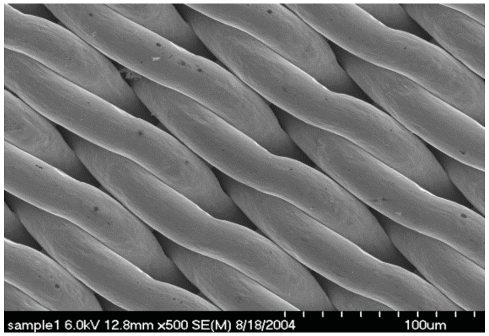
- Full "communication" device – usually a fine mesh or vane alongside tank wall
- Micron sized pores in screen separate phases and wick liquid into channel



Screen Channel Liquid Acquisition Devices

- Screen channel liquid acquisition devices (LADs) or gallery arms are best in multi-directional, multi-g environments, high flow rates
- Warp/shute wires characterize the mesh (ex. 325x2300)
- LADs rely on capillary flow, wicking, and surface tension forces to maintain liquid flow





- Screen channel LADs fail when vapor is ingested across the screen during liquid outflow: $\Delta P_{total} > \Delta P_{BP}$

- Differential pressure across a screen pore that overcomes the surface tension of the liquid at that pore:

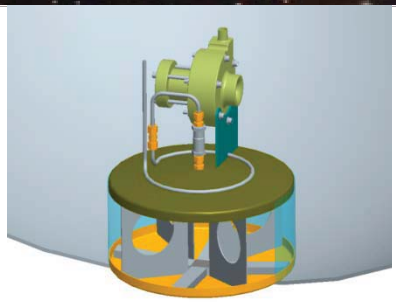
$$\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}$$

- Small pore diameters (< 20 µm) are favorable for LH_2 systems to counter low surface tension (2 mN/m)
- LH2 Normal Boiling Point (NBP) bubble point of a 325x2300 screen is only 575 Pa (0.08 psi)

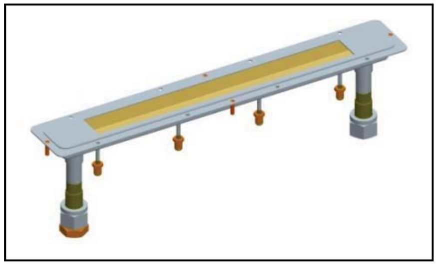
Low-g Liquid Acquisition

Prior Accomplishments:

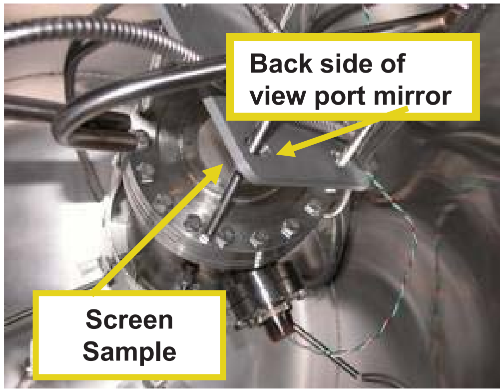
- Measurement of bubble point (breakthrough) pressure for saturated LCH4 completed CCL-7 2007.
- Measurement of bubble point (breakthrough) pressure for saturated LOX completed CCL-7 2008.
- Measurement of bubble point at elevated temperature and pressure conditions for LO2 and LCH4. 2010
- Conducted outflow tests at representative flow conditions for main engine burns to assess pressure drop across the screen channel LAD and to determine the breakthrough pressure at those conditions 2010



Screened Sump Conceptual Design for Lunar Lander Ascent Stage

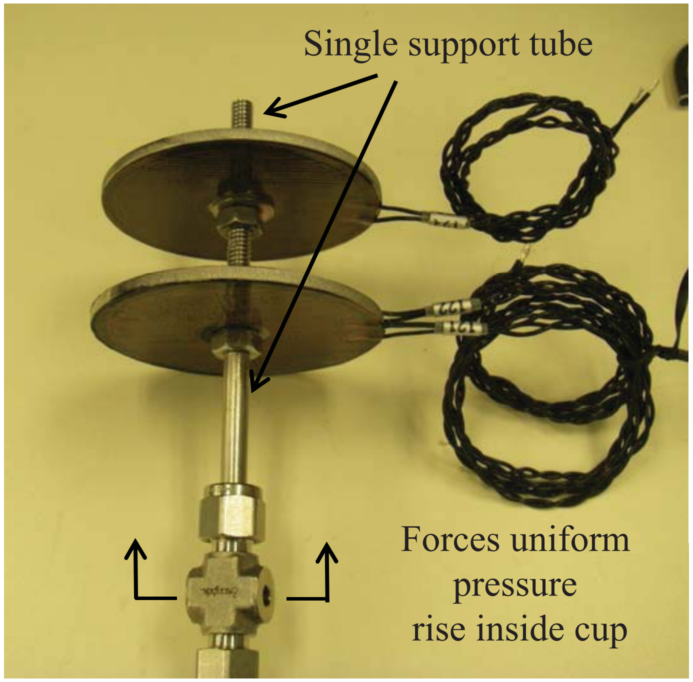


High Flow rate LAD Channel Design



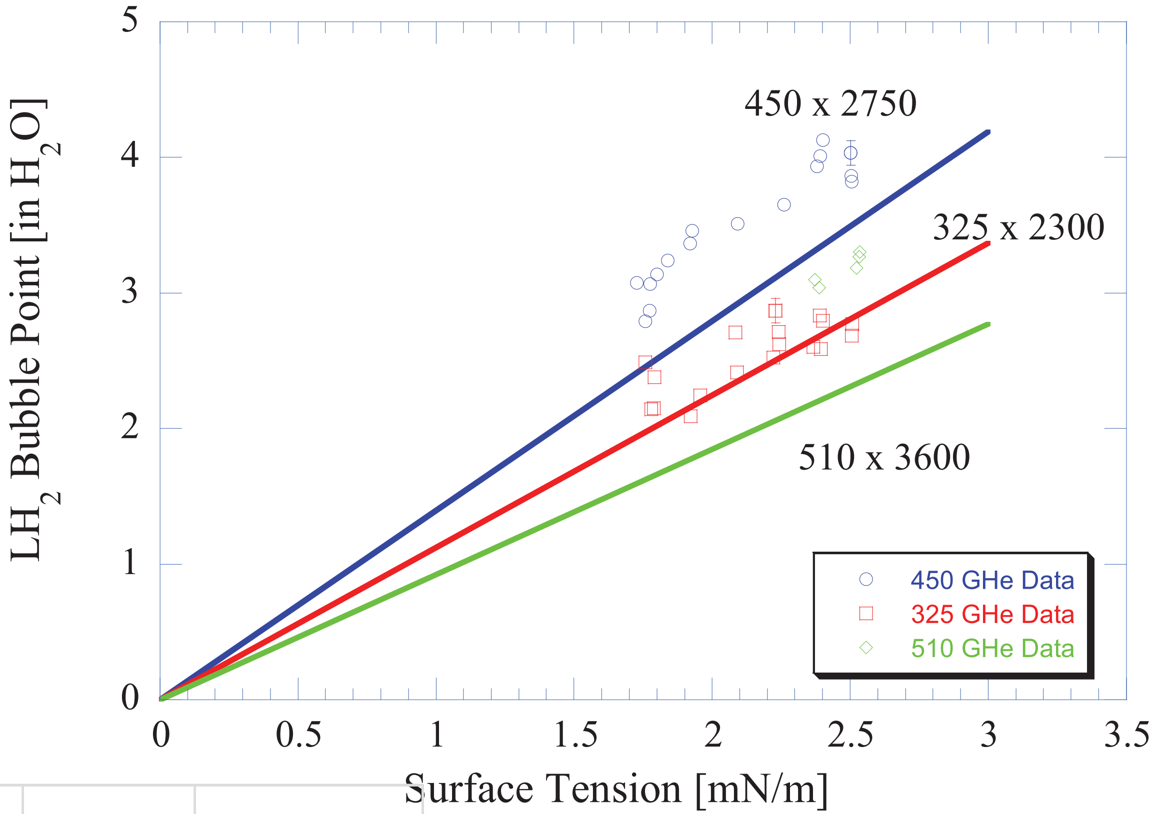
Test fixture (CCL-7) for bubble point pressure

Static LAD Bubble Point screen/cup



Effect of Screen Mesh on Static Bubble Point

- LH_2 near normal boiling point
- GHe temperature near screen close liquid temperature for all points
- 450x2750 buys >25% margin over the 325x2300 screen (based on comparison of test data curve fits)
- 510x3600 prediction curve and data both lie below 450 data

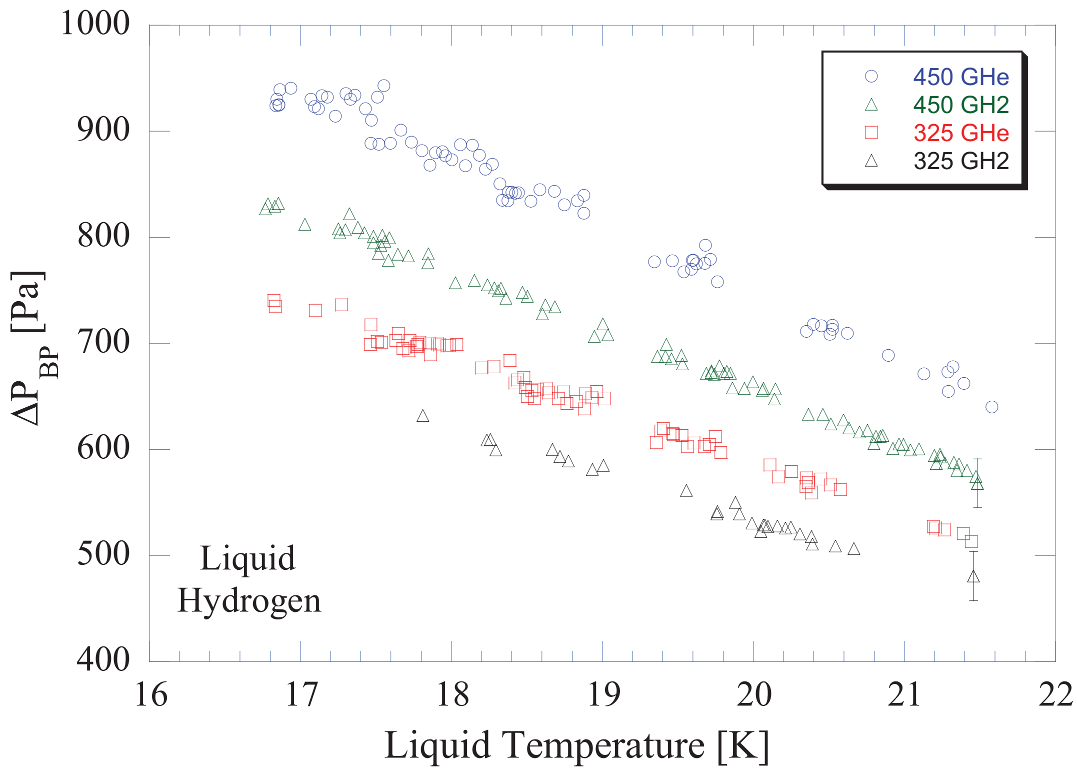


	Room Temperature					
Screen	Pore Diameter [µm]	# warp	# shute	d warp [µm]	d shute [µm]	Absolute µ rating
325x2300	14.8	325	2300	38.1	25.4	8 to 9
450x2750	11.8	450	2750	26	20	6 to 7
510x3600	15.9	510	3600	26	15.2	5 to 6

There may be an optimal warp to shute diameter ratio which maximizes bubble point pressure

Effect of Temperature, Pressurant Gas Type

$$\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}$$



- ***Rigorous parametric investigation of influential parameters on LH2 LAD performance (Hartwig et al. 2013)***
    1. ***Mesh***
    2. ***Liquid***
    3. ***Liquid Temperature***
    4. ***Liquid Pressure***
    5. ***Pressurant Gas Type***
    6. ***Pressurant Gas Temperature***

- **ΔP_{BP} sets upper limit on performance**
- **450 ΔP_{BP} scales inversely with liquid temp. Subcool w/ GHe yields an average 39% difference over GH2 pressurization**
- **4/6 parameters summarized here**
- **For all points here, $T_{GAS} = T_{LIQUID}$**

Recent Full Scale LH2 LAD Outflow Tests

Objective:

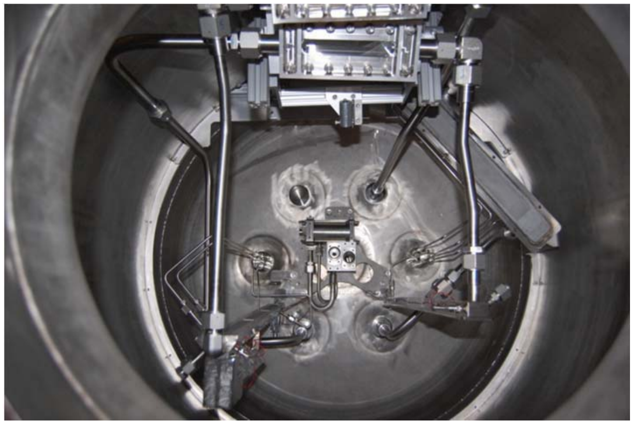
- Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow
- Quantify LAD breakdown as a function of liquid temperature, LAD outflow rate

Significance:

- Completed over 100 flow through screen tests, as well as gaseous helium calibration, further analysis is required to eliminate anomalous tests from the results.
- Completed over 20 Inverted Outflow LAD breakdown tests; Thermodynamic Vent System (TVS) cooled LAD shows superior performance

Test Tank

Flight Representative LAD Installed



Top Down View

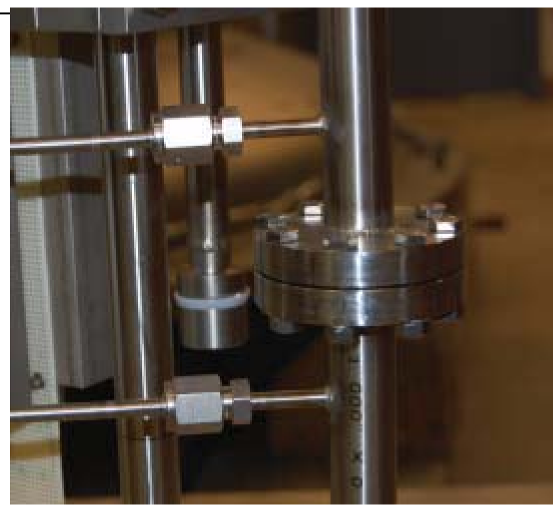
Flow-through-Screen Research Hardware

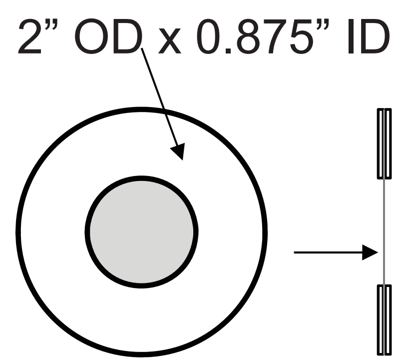
<u>Hardware Configuration</u>

- Flow-through-screen hardware mounted on test tank lid
- 2 screens mounted in series (450x2750, 325x2300)
- Flow routed vertically upward
- Screens spaced out to overcome entrance effects @ highest flow rates @ second screen
- Multiple DPTs for each screen to cover flow range
- 2 Venturi flow meters (FMs) used to measure flow
- Both screens passed pretest Isopropyl Alcohol (IPA) bubble point test

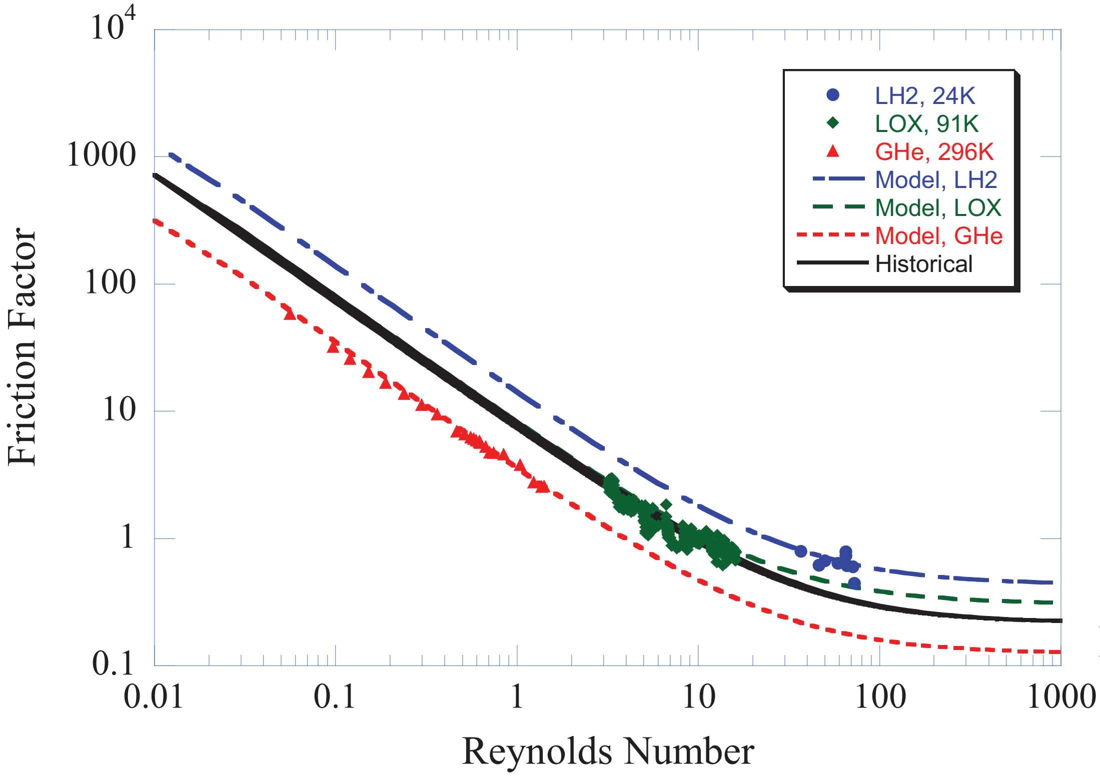
325x2300

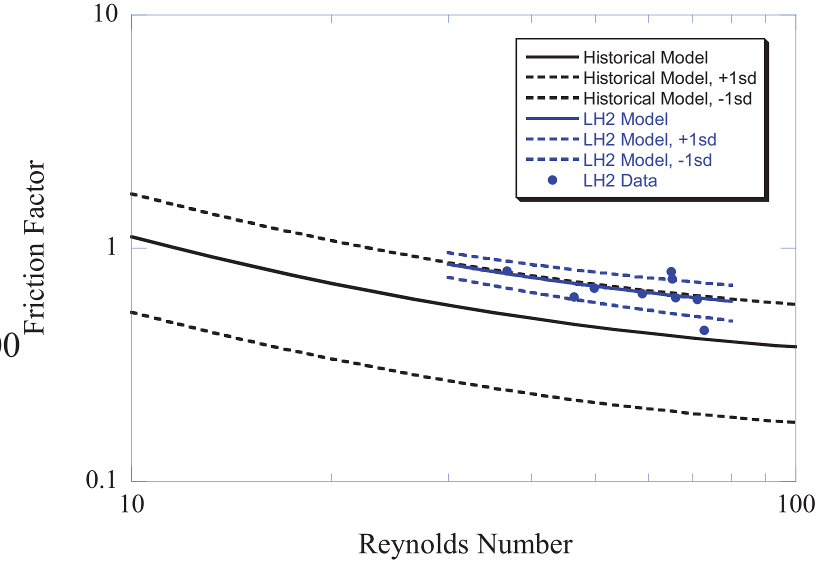
450x2750





Temperature Dependence of ΔP_{FTS}



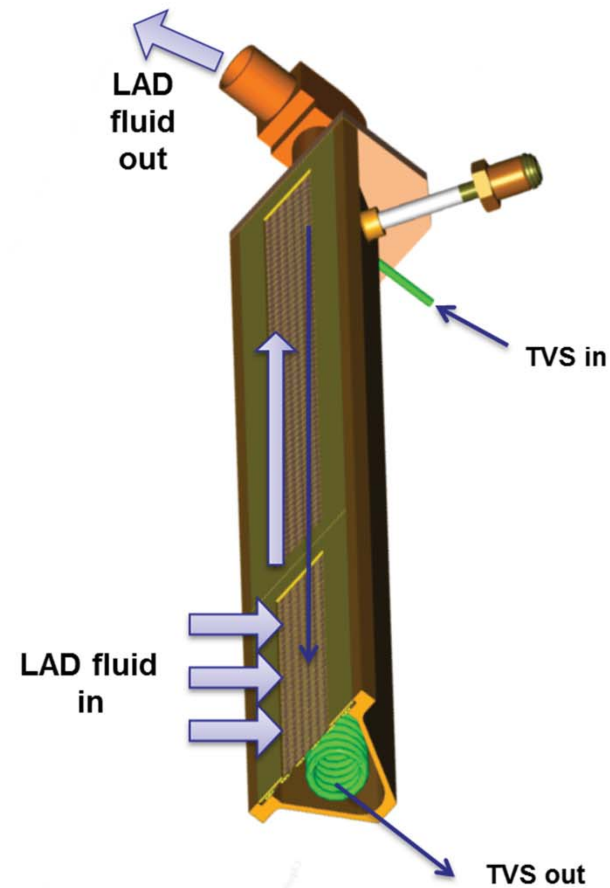


- **All data is for exact same 325x2300 screen sample**
- **Our Ghe and LH2 data bound the single Armour and Cannon (A&C) curve fit to historical data**
  - Important to note that A&C prediction based on multiple screen styles (square, Dutch Twill) and gases
- **Evidence that ΔP FTS may be temperature dependent (higher flow losses at LH2 temps due to possible screen shrinkage)**

325x2300 TVS Cooled LAD

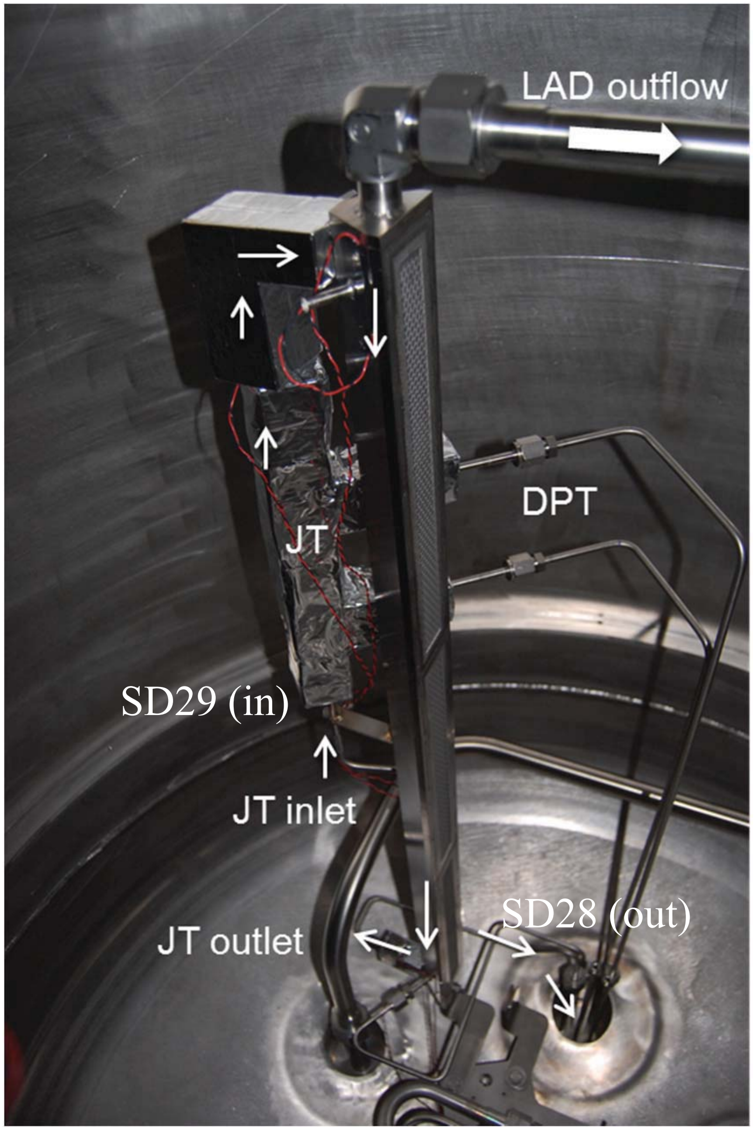
- From previous LOX, LCH4, LH2 bubble point tests, cooling the liquid at the screen lowers T, increases γ, increases ΔP_{BP}
- Gain in ΔP_{BP} should translate into lower breakdown heights

- Triangular backed
  - Room for heat exchanger
  - Match hydraulic diameters
- Perforated plate backed screens
  - Enhanced wicking
  - Added structural support against launch loads
  - Cost: reduces to 63% screen open area

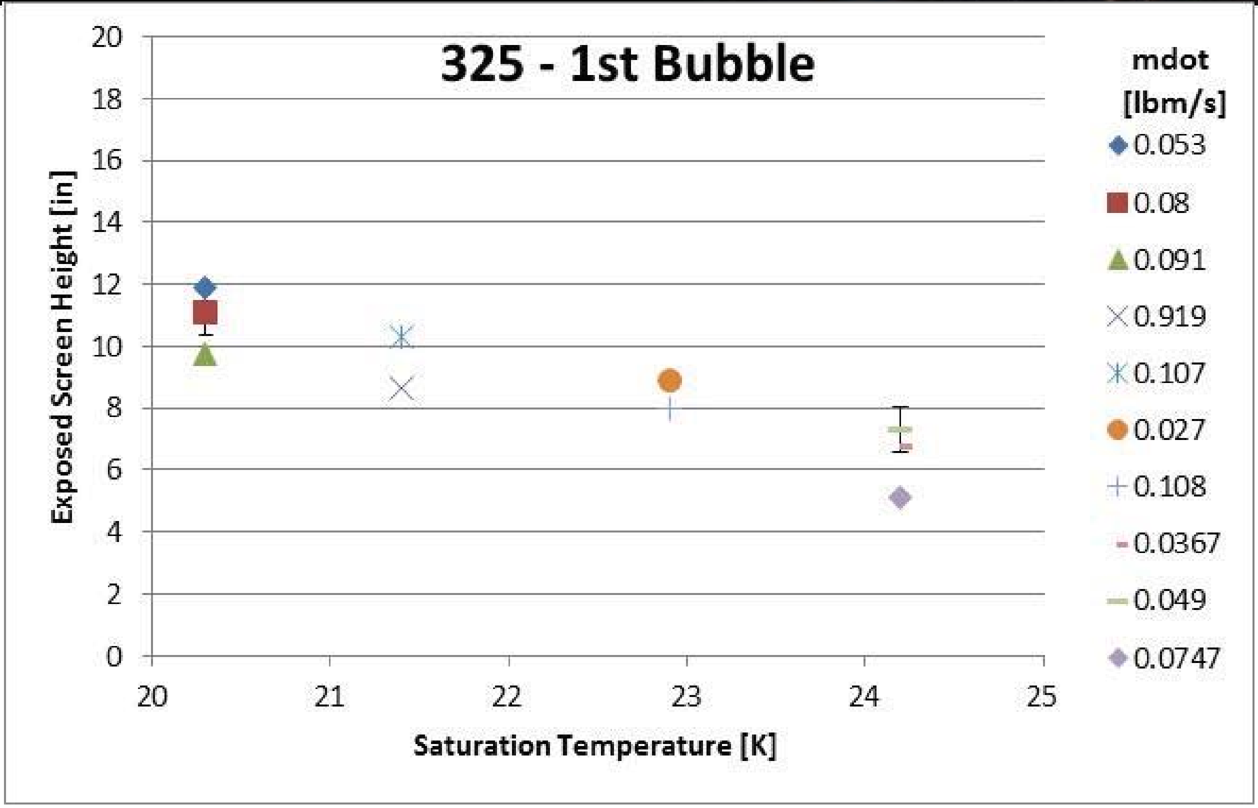


325x2300 TVS Cooled LAD Principle of Operation

- Small amount of fluid is drawn from the tank, expanded across a JT orifice (constant enthalpy), thus cooled and circulated through the flight-like LAD as counterflow HEX to cool the fluid inside the LAD
- HEX designed to flash inside cooling coil inside LAD
- Measure DPT across JT, dT across TVS
- LAD originally designed to cool LH2 inside channel 6°R @ 50 psia saturated liquid at a JT flow rate of ~0.0025 lbm/s (< 6.67% of lowest LAD outflow rate)



325x2300 Standard Channel



- Performance measured in terms of exposed screen length from top of channel
- Could also consider exposed screen length
- LAD breaks down when

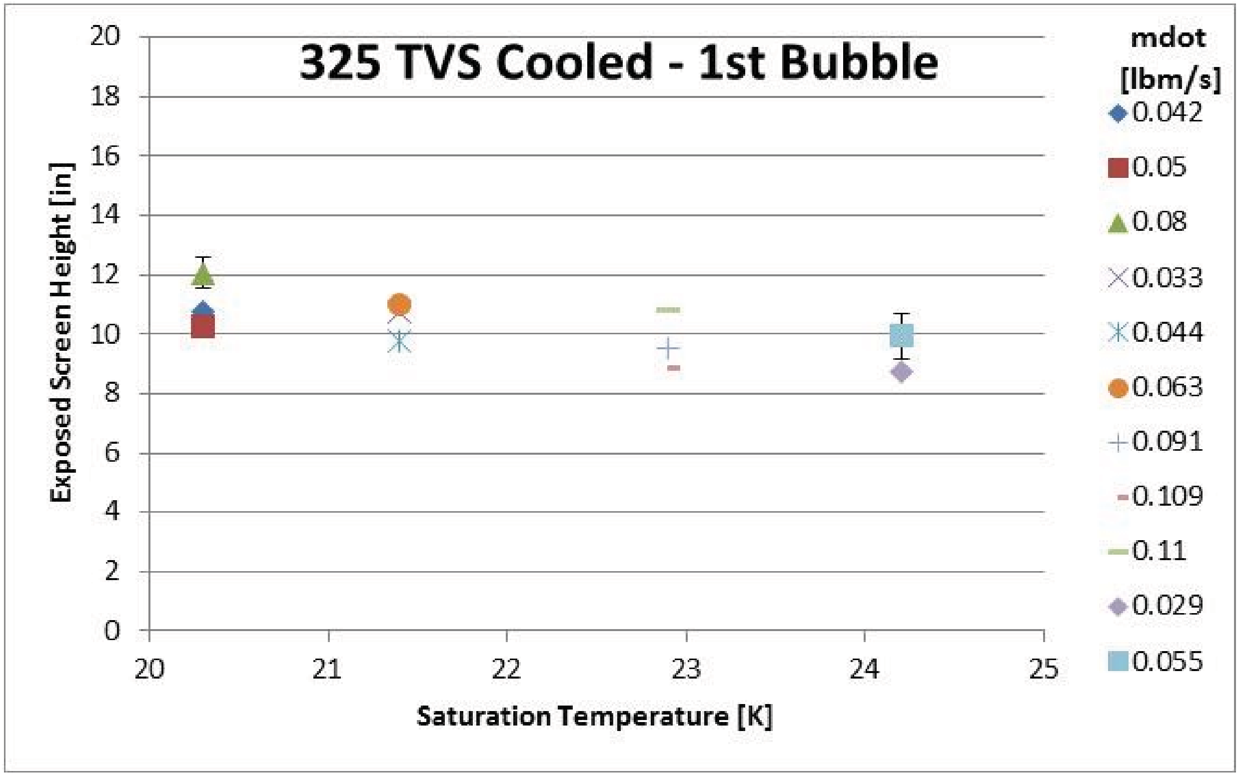
$$\Delta P_{total} > \Delta P_{BP}$$

- "Breakdown" = ingestion of a single GHe bubble

Trends

- Breakdown height scales linearly with liquid temperature (earlier breakdown in warmer liquid)
- Breakdown height scales with flow rate (earlier breakdown @ higher flows)
- Data correlates well with model

325x2300 Flight Channel

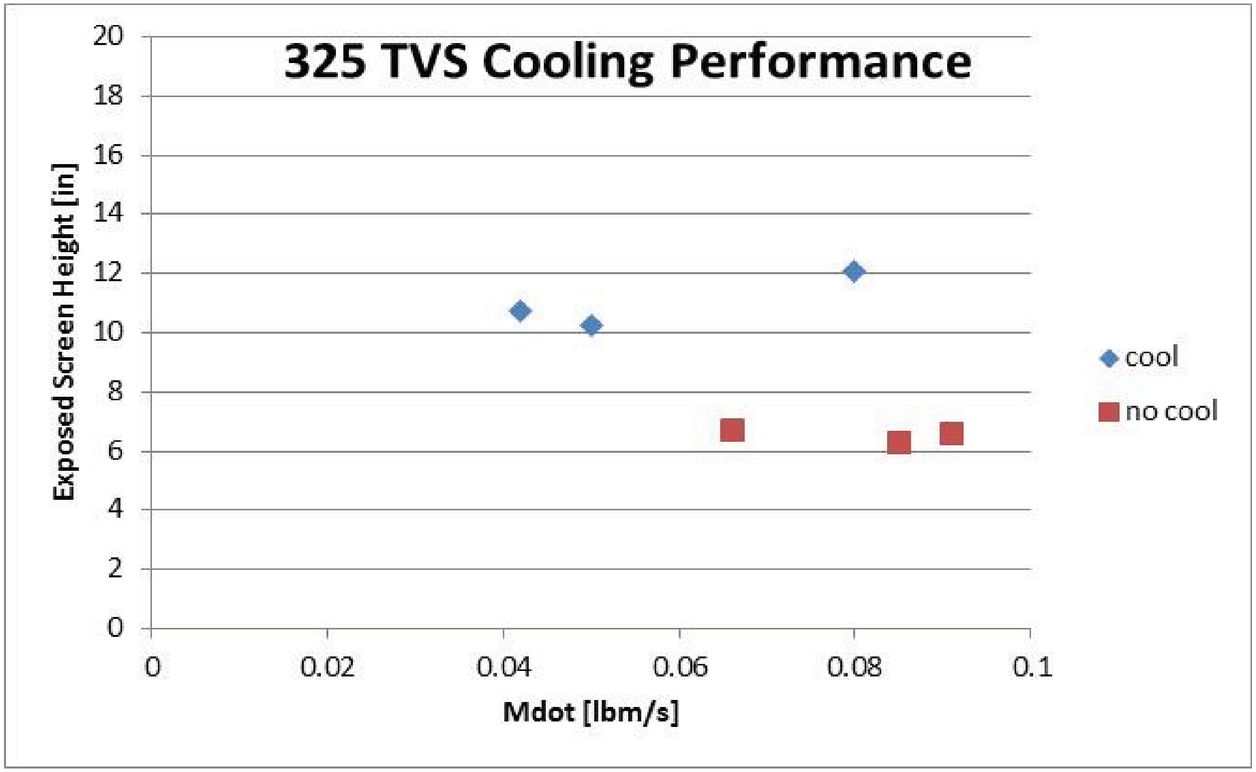


Trends

- **Breakdown height scales with liquid temperature (earlier breakdown in warmer liquid)**
- **Breakdown height scales inversely with flow rate (later breakdown @ higher flows)**
- **Data doesn't correlates well with model**

- **TVS cooling flattens temperature dependence**
- **Perforated plate enhances wicking**

325x2300 LAD TVS Performance



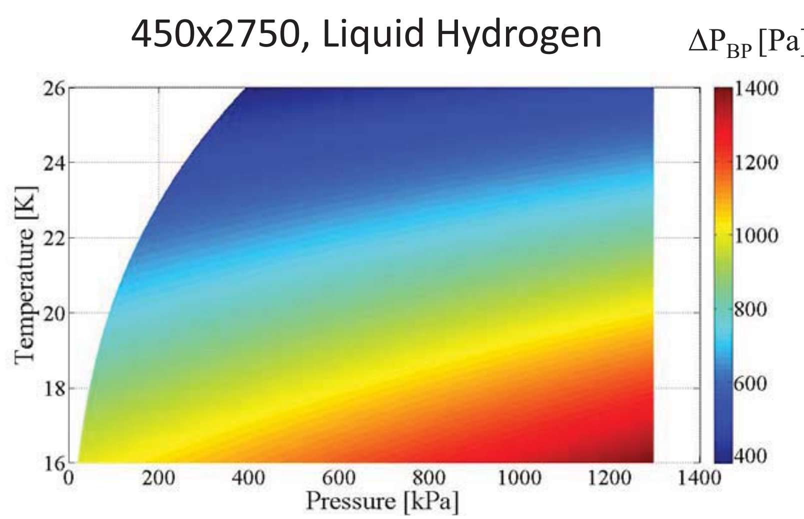
- **All six tests in 15 psia saturated liquid**
- **3 tests with TVS engaged/3 tests off**

<u>Trends</u>

- **TVS improves performance of 325x2300 Flight LAD by an average 4.9% of total LAD length in 15 psia sat. liquid**

Cryogenic Bubble Point Pressure Model

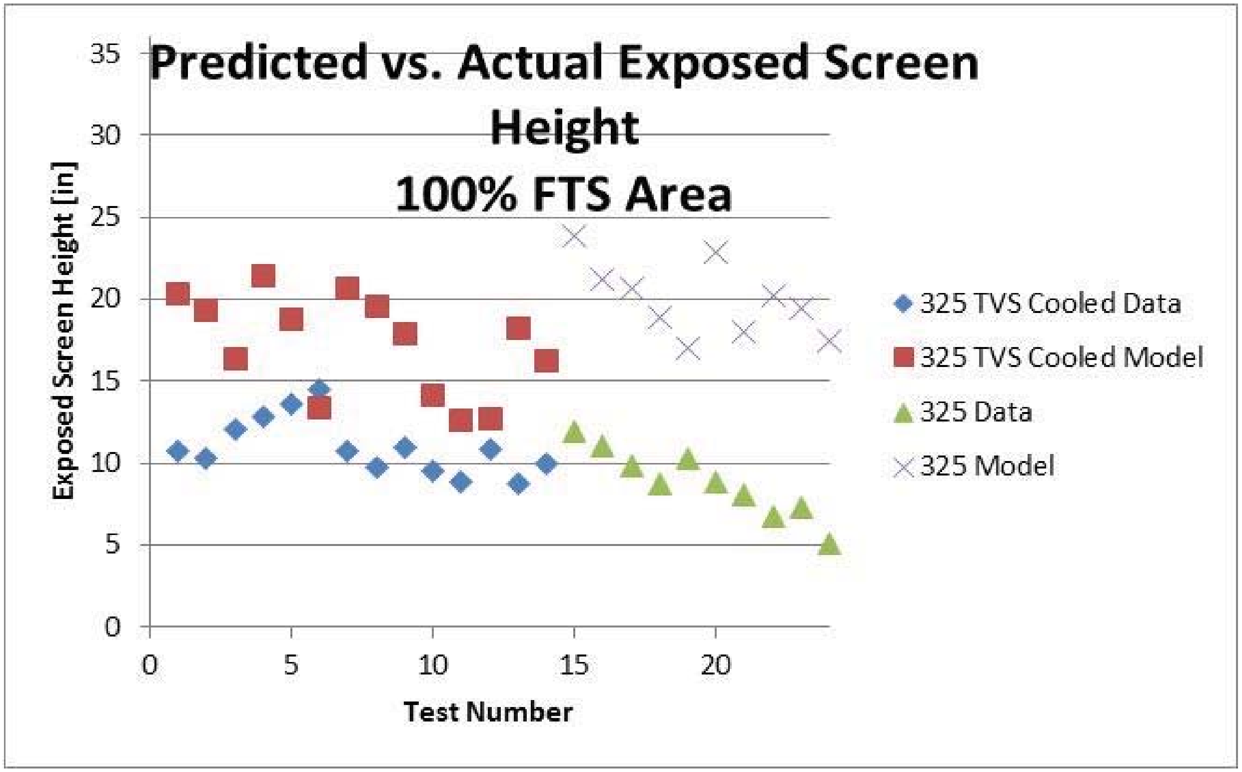
- **Model determines static bubble point pressure for any screen, liquid, operating temperature and pressure, and pressurant gas type and temperature**
- **Model anchored to data (semi-analytical, semi-empirical)**
- **Accounts for:**
  - Updated surface tension model
  - Temperature dependent pore diameter
  - Differences between pressurization schemes
  - Effect of subcooling the liquid
  - Effect of raising the pressurant gas temperature (relative to liquid)



$$\Delta P_{BP}\left(screen, T, P, T_{gas}\right) = \frac{4\gamma\cos\theta}{D_P\left(T\right)} n_1\left(gas, T\right)\left(1 + n_2\left(gas\right)\frac{P - P_{SAT}\left(T\right)}{P_{REF}}\right)\left(1 - n_3\left(gas\right)\frac{T_{GAS} - T}{T_{REF}}\right)$$

- n_1, n_2, n_3, constants

Inverted Outflow Data vs. Model



- **325 TVS cooled outperforms 325, despite post-test degraded performance in IPA**
- **Disparity between data and model due to:**

1. % area in FTS term

$$\Delta P_{FTS} \propto \frac{1}{A_C}$$

less flow area = more ΔP_{FTS} → shift the data up

2. Degradation in performance from pre to post IPA tests

Findings and Recommendations

Summary of Results – LADs

1. Bubble point scales with the mesh of the screen for 325x2300 and 450x2750 screens.
   - 450 buys us 27% margin over 325 => higher flow rates during transfer
   - Pore diameter is both screen and temperature dependent
2. Bubble point scales with the surface tension of the liquid
3. Ghe pressurization = gain factor; GH2 pressurization = degradation factor
4. ΔP_{FTS} is temperature dependent, as is the bubble point pressure
   - $\Delta P_{FTS,450} < \Delta P_{FTS,\,325}$. $\Delta P_{BP,450} > \Delta P_{BP,325}$. Hints at existence of optimized mesh for low surface tension liquid acquisition. (desire for flight is highest for ΔP_{BP} for lowest ΔP_{FTS}).
5. Frictional and Dynamic pressure losses also higher than anticipated @ LH2 temps.
6. Inverted vertical outflow breakdown point dominated by liquid temp; second order dependence on liquid outflow rate
   - TVS cooling always improves performance (cooling supports higher outflow rates)
   - Subcooling + pressurizing w/ GHe always improves performance (9% in 15 psia saturated liquid)

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